

## PUPILLOMETRIC MEASUREMENT OF OPERATOR WORKLOAD

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Operator workload and its assessment is a major issue in human performance theory. It is intuitively compelling to hold that some mental operations demand more of the operator than do others. We speak easily of attention-demanding tasks and tasks that can be performed "in one's sleep." Yet we know very little about what these demands might be, what the structure or structures are upon which such demands are placed, and, not surprisingly, we have reached little consensus as to how processing load might be measured. In this paper, I shall describe one approach to the workload measurement, pupillometry. Pupillometric measures provide an indication of momentary fluctuations in central nervous system excitability that occur as cognitive operations are performed; the magnitude of these changes may serve as a sensitive indicator of the workload imposed by cognitive tasks.

## PUPILLOMETRY

Pupillometry utilizes optical measurement methods to determine the diameter of the pupil of the eye. Photographic measurements were employed in early pupillometric experiments; now electronic video pupillometry is commonly used. These instruments, such as the G and W Applied Science Laboratories television pupillometer, process an infrared video image of the eye to extract either vertical pupillary diameter or, in some cases, pupil area. This value is recomputed 30 times each second. In simpler systems a headrest is used to stabilize the position of the pupil in space; more complex systems allow free head movement and track the position of the eye using a second, larger video image to control a servomechanism that aims the pupil video camera. Such instruments have been installed recently in aircraft cockpit simulators.

In our laboratory, the output of the pupillometer is sampled and stored by computer for later analysis. Three standard programs are utilized: the first performs an inspection of the data, correcting trials with minor artifacts and rejecting trials with more seriously contaminated data; the second program averages trials together, sorting by stimulus and response codes as appropriate; the third computes the changes in pupillary diameter over specified segments of the trial from

the averaged task-evoked pupillary responses. Similar procedures are employed in other laboratories.

#### PHYSIOLOGICAL CONTROL OF PUPILLARY MOVEMENTS

Pupillary diameter is determined by the relative strengths of contraction of the two opposing muscle groups of the iris, the dilator and sphincter pupillae. The dilator muscles are radially oriented bands of smooth muscle that are innervated by the sympathetic branch of the autonomic nervous system. Contraction of these muscles dilates the pupil. Conversely, the sphincter pupillae are innervated by the parasympathetic system and act to close the pupil when activated. Pupillary dilation, therefore, can result from either sympathetic excitation or parasympathetic inhibition. Both these pathways are affected by activation of nuclei comprising the reticular activating system of the brainstem; thus, pupillary movements are used in classical neurophysiology to measure the activation of these reticular nuclei (Moruzzi, 1972).

Although the details of the interaction of the reticular core with higher brain regions are only poorly understood at present (Hobson and Brazier, 1980), there is little doubt that cortico-reticular and reticulo-cortical interactions play a major role in determining the dynamics of higher brain functions. Most commonly the reticular system is viewed as serving an energizing function for the cortex (Luria, 1973), but it is perhaps wise to regard this viewpoint as a metaphor. Nonetheless, the ideas that pupillary movements reflect reticular activation and that reticular activation controls the dynamics of cognitive processing provide a theoretical basis for the use of pupillometry in the study of mental workload.

#### WITHIN-TASK VARIATIONS IN PROCESSING LOAD

The amplitude of the task-evoked pupillary response has been shown to reflect variations of processing load within a wide variety of cognitive tasks. Some examples are the following.

Memory. One of the first clear demonstrations that pupillary diameter varies with processing load was found in the study of short-term memory (Kahneman and Beatty, 1966; Kahneman, Beatty and Pollack, 1967). In simple short-term recall of digit strings, as when being told a telephone number and then dialing it, a characteristic pattern of pupillary movements are observed. Pupil diameter increases systematically as each digit is heard, reaching a maximum dilation in the interval before report (subjects in these experiments repeated the digit strings at the rate of 1/sec rather than dialing a telephone). Furthermore, the size of the peak dilation between listening and report is a monotonic function of the number of items heard (3 to 7 digits). During report, the pupil constricts with each digit spoken, reaching baseline diameter at the completion of the task. Such effects are highly reliable; they occur in every subject and are remarkably

consistent in magnitude. The dilation for 7 digits is approximately 0.5 mm.

The slope of these task-evoked pupillary responses is determined by the difficulty of the to-be-remembered information. For example, the memory span for unrelated nouns is shorter than that for digits; it is said, therefore, that the nouns place larger demands on the processing system than do digits. Thus, it is not surprising that the magnitude of pupillary dilation for individual items is greater for nouns than digits (Kahneman and Beatty, 1966).

A third important feature of the task-evoked pupillary response in the short-term memory task is that it increases with items presented only within the range of possible performance; when further demands are placed upon the processing system no additional dilation is observed. This important finding was first reported by Peavler (1974), who measured the task-evoked pupillary response for string lengths greater than the memory span. For most individuals, by the way, the span for digits is about 7 items. When longer strings are presented, errors begin to occur (Miller, 1956). Peavler found that when superspan strings were presented, the pupil dilated with each item until the seventh; subsequent items elicited no further dilation. This saturation of the pupillary response at the limit of capacity has been verified subsequently by other workers.

The short-term memory task provides a particularly clear demonstration of the properties of the pupillary response as a measure of mental workload. Manipulations that should increase load, here item type and number of items, increase the amplitude of the response in an orderly manner. Increases in processing demands beyond the capacity of the system to respond are not reflected in pupillary movements. The task-evoked pupillary response indexes the processing demands being met by the system, not the demands placed upon the system by the task. Thus, it may serve as a measure of mental work executed, at least within the confines of a particular task.

Language. A number of levels of language processing have been studied pupillometrically. Beatty and Wagoner (1978) showed that the degree of processing required in a simple letter matching task was faithfully reflected in the magnitude of the task-evoked pupillary response. The smallest dilations occurred when only matching of physical details was required to reach a judgement of "same", as for the letter pair "AA". When name code extraction was required (as for "Aa") the pupillary response was significantly enhanced. But in both cases the response was relatively small, on the order of 0.1 mm.

Larger responses were observed by Ahern and Beatty (1981) in a word matching task, in which individuals heard two words and were required to determine if they shared the same meaning. The word pairs, which were drawn from psychometric tests of intelligence, varied in difficulty. Difficulty level was reflected in the amplitude of the task-evoked pupillary responses.

The largest responses for language processing were obtained with a grammatical reasoning task (Baddeley, 1968). Subjects listened to sentences of the form "A follows (precedes) B" and then heard an exemplar letter pair ("BA"); the task was to determine if the sentence correctly describes the pair. The sentences varied in grammatical form, beir active or passive and positive or negated. A significant effect of ammatical complexity was observed. Response were approximately 0.5 mm. in amplitude (Ahern and Beatty, 1981).

Other tasks. Pupillometric investigations have also been reported for a variety of other types of tasks, including simple sensory and motor tasks. Although space does not permit a summary of these results, they support the conclusion that the task-evoked pupillary response is a sensitive and accurate physiological measure of within task variations in processing load.

#### BETWEEN-TASK VARIATIONS IN PROCESSING LOAD

But any useful measure of operator workload must do more than reflect within-task variations in processing load; it must, in addition, provide a measure of workload imposed by qualitatively different mental operations. Only in this way can operator workload be assessed in complex man/machine systems.

Evidence that the task-evoked pupillary response is sensitive to variations in processing load imposed by qualitatively different mental operations has been provided in a detailed review by Beatty (in press). From the published literature, all data were employed that met two criteria; there were no motor responses occurring during measurement and the published figures permitted estimation of the maximum value of the pupillary response. The resulting data were remarkably consistent, leading to the conclusion that the task-evoked pupillary response provides a reliable and reasonable indication of the processing load imposed by cognitive tasks that differ markedly in their internal structures.

#### BETWEEN-INDIVIDUAL VARIATIONS IN PROCESSING LOAD

Finally, there is evidence that the amplitude of the task-evoked pupillary response provides an indication of differences in processing load imposed by the same task on individuals who differ in cognitive abilities. Ahern and Beatty (1979, 1981), for example, measured pupillary responses while solving multiplication problems in university student with high and low Scholastic Aptitude Test scores. The high-scoring students showed significantly smaller pupillary responses at all difficulty levels. Further, the amplitude of these responses correlated only with ability measures and not with personality variables or psychometric measures of state or trait anxiety. Finally, there was no difference between groups in the amplitude of the light and dark pupillary reflexes. These data support the view that solving the same objective multiplication problem (e.g., 6 time 8) is a more demanding

task for the less able students.

#### SUMMARY

All available evidence supports the view that the amplitude of the task-evoked pupillary response provides a sensitive indicator of the workload imposed by mental operations. However, much remains to be learned. We do not understand with any certainty the physiological mechanisms linking the autonomic periphery with the highest levels of central nervous system function. We know little about the ways in which these responses, or other similar physiological measures, may be applied to the solution of practical design problems facing human factors engineering. But the future appears promising; pupillary movements may provide one key for providing a solid empirical basis for the problem of operator workload assessment.

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